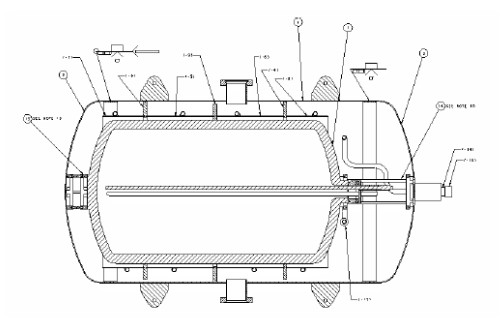
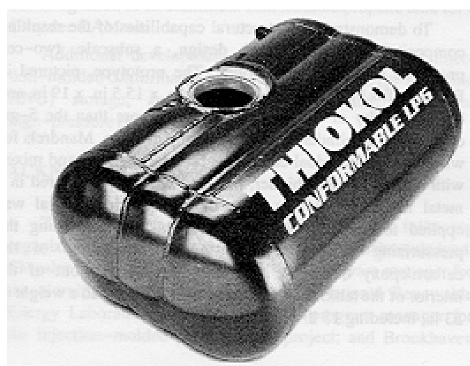
Workshop on Compressed and Liquefied Hydrogen Storage

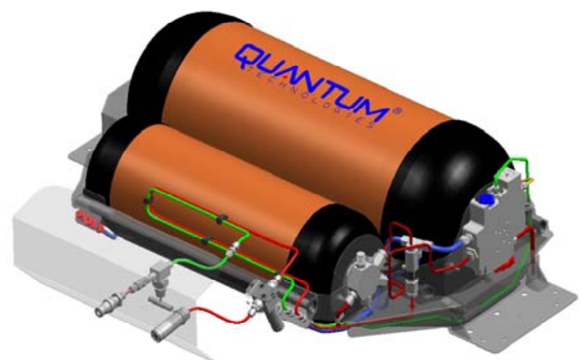
Proceedings

October 16th, 2002
Hosted by U.S. Council for Automotive Research (USCAR)
Southfield, MI

Sponsored by the
U.S. Department of Energy
Office of Hydrogen, Fuel Cells and Infrastructure Technologies







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Acknowledgments

We would like to thank the U.S. Council for Automotive Research (USCAR) for hosting this workshop, especially Ms. Kathy Brownston who arranged for the meeting and facilities and recorded the highlights of the workshop. We also appreciate the efforts of Dr. Walt Podolski of Argonne National Laboratory and Mr. Brian James of Directed Technologies, Inc., who organized the workshop. We thank the workshop participants from industry and the national laboratories for their contributions. Your input will be invaluable as we move forward with our R&D plan.

Dr. JoAnn Milliken
Hydrogen Storage Team Leader
Office of Hydrogen, Fuel Cells and Infrastructure Technologies
U.S. Department of Energy

Overview

The President's National Energy Policy, issued in May 2001, directs the Secretary of Energy "to develop next generation technology including hydrogen" and to "focus research and development efforts on integrating current programs regarding hydrogen technologies, fuel cells and distribution." In response, the U.S. Department of Energy (DOE) initiated a National Hydrogen Vision and Roadmap process through which it sought the guidance of stakeholders from industry, academia and the nonprofit sector on the vision and on the technical content of a robust R&D program in this crucial area. The National Hydrogen Roadmap clearly identified hydrogen storage as an issue critical to realizing a hydrogen economy. In particular, on-board hydrogen storage is recognized as a key enabling technology for automotive fuel cell systems. The National Hydrogen Roadmap can be downloaded from http://www.eere.energy.gov/hydrogenandfuelcells/. Figure 1 illustrates how policy documents and stakeholder input from the visioning and road-mapping processes have been incorporated into the DOE planning activities. The Office of Hydrogen, Fuel Cells and Infrastructure Technologies Multi-Year Research, Development and Demonstration Plan is built upon these and other predecessor planning documents and is also integrated with other DOE Office hydrogen development plans.

FIGURE 1. THE DOE HYDROGEN, FUEL CELLS AND INFRASTRUCTURE TECHNOLOGIES PROGRAM PLAN BUILDS UPON SEVERAL PLANNING DOCUMENTS

The Hydrogen, Fuel Cells and Infrastructure Technologies Program within the DOE Office of Energy Efficiency and Renewable Energy plans to create a national hydrogen storage project. A workshop on compressed and liquefied hydrogen storage was a step in identifying a path forward. Technical experts from industry and the national laboratories were assembled to identify the current status of compressed and liquefied hydrogen storage technologies, to solicit new ideas and to rank priorities for R&D efforts. Ten technical experts convened at U.S. Council for Automotive Research (USCAR) on October 16, 2002 for the Workshop on Compressed and Liquefied Hydrogen Storage. A list of participants is included in Appendix 1. The output of this workshop will be used to develop a multi-year plan for the DOE Program. These proceedings describe the results of this workshop.

Safe, cost-effective and practical means of storing hydrogen is an important component if hydrogen is to emerge as a practical option in the Nation's energy infrastructure. Significant technical barriers remain for safe, cost-effective hydrogen storage systems, particularly on-board for transportation applications.

Workshop Organization

The workshop included two plenary presentations. The first presented an overview and the goals of the DOE Hydrogen, Fuel Cells and Infrastructure Technologies Program. In addition, the findings of the DOE Workshop on Hydrogen Storage Materials were reviewed. The second presentation described the design of a generic high-pressure, composite storage tank. The assumptions that were made in the design served as the point of departure for discussions relating to performance and to cost of high-pressure hydrogen storage tanks.

Following the plenary presentations, the participants discussed technology status, barriers and issues related to widespread use of high-pressure and cryogenic storage systems on board vehicles. The participants reached a consensus on the relative ranking of R&D needs and recommended programs to address the issues.

Workshop Objectives

The overall goal of the workshop was to obtain technical input to shape a national activity and to be included as part of a DOE multi-year R&D plan. Specifically, the workshop participants were asked to address the following issues:

- Review the current status of compressed and liquefied hydrogen storage technologies
- Identify the technical challenges that must be overcome to meet the goals of the FreedomCAR partnership
- Identify promising technical approaches to overcome the challenges
- Prioritize the R&D needs for each of the technical approaches

Plenary Session - Introduction and Overview Presentations

The overview presentation and the high-pressure hydrogen storage tank status presentation are included at the end of the proceedings.

Overview of the DOE Program

Dr. Podolski of Argonne National Laboratory provided an overview of the DOE activities in hydrogen and fuel cell technologies in the following areas: (1) the Hydrogen, Fuel Cells and Infrastructure Technologies Program; (2) the Role of FreedomCAR; (3) R&D

Priorities; (4) DOE Fuel Cell & Hydrogen Activities; (5) DOE Targets/Status and (6) DOE Hydrogen Storage Materials Workshop review.

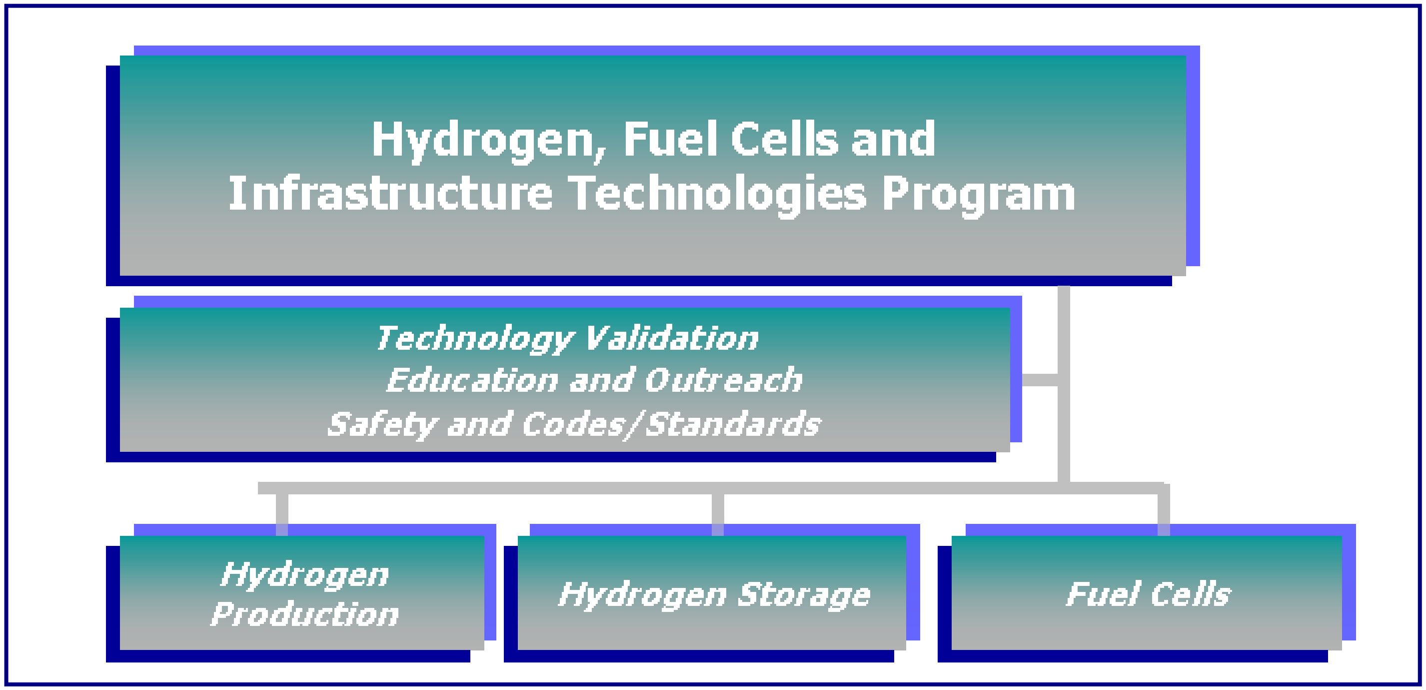
The Hydrogen, Fuel Cells and Infrastructure Technologies Program

The DOE Hydrogen, Fuel Cells and Infrastructure Technologies Program was created to implement the directive in the National Energy Policy to "focus research and development efforts on integrating current programs regarding hydrogen, fuel cells and distribution…." Three technical teams will implement R&D based on the objectives of the program. These are the Fuel Cell, Hydrogen Storage and Hydrogen Production teams. In addition to these three technical teams, cross cutting programs will be implemented including efforts in the area of safety/codes and standards, technology validation and education. An organization chart of the DOE program is shown below in Figure 2.

Role of FreedomCAR and the President's Hydrogen Fuel Initiatives

FreedomCAR's long-term goal is to develop advanced automotive technologies, which will require no foreign oil and emit no harmful pollutants or greenhouse gases. Specifically, the FreedomCAR partnership is focusing on developing technologies to enable mass production of affordable hydrogen-powered fuel cell vehicles. The Hydrogen Fuel Initiative is designed to accelerate development of advanced technologies for producing, delivering, storing and using hydrogen.

FIGURE 2. HYDROGEN, FUEL CELLS AND INFRASTRUCTURE TECHNOLOGIES PROGRAM ORGANIZATION



DOE Fuel Cell & Hydrogen Activities

The Hydrogen Vision and Roadmap Workshops were held in November 2001 and April 2002, respectively, and included the participation of a wide spectrum of stakeholders. The results of these workshops were incorporated into the National Hydrogen Roadmap, which can be downloaded from http://www.eere.energy.gov/hydrogenandfuelcells/.

The DOE program focuses its R&D activities on removing high-risk technical barriers. In Fiscal-Year 2002, fuel cell activities were funded at $47 million, while the hydrogen activities were funded at $29 million. Funding appropriations for Fiscal-Year 2003 represent a 19 percent increase in fuel cell technology R&D and a 38 percent increase for hydrogen technology. Request for Fiscal-Year 2004 funding will be $88.0 million for hydrogen technology R&D and $77.5 million for fuel cell technology R&D.

DOE Performance Targets/Status

Through the FreedomCAR partnership, DOE established R&D targets for hydrogen storage, see Table 1. The primary focus of the program is on-board transportation applications since these are technically more challenging compared to off-board storage of hydrogen. These targets have been revised to reflect the Administration's emphasis on the transition to a hydrogen economy. Note, DOE technical targets are based on vehicle requirements and do not differentiate between chemical and physical forms of hydrogen storage. This table lists the targets as of June 2003. Minor changes may be made as the targets are analyzed and updated. Updated targets will be included in the hydrogen storage solicitation to be released in July 2003.

TABLE 1. DOE TECHNICAL TARGETS, ON-BOARD HYDROGEN STORAGE SYSTEMS

TECHNICAL TARGETS, ON-BOARD HYDROGEN STORAGE SYSTEMS [a, b, c]				
STORAGE PARAMETER	UNITS	2005	2010	2015
Usable, specific-energy from H_2 (net useful energy/max system mass)[d]	kWh/kg ($kg\ H_2/kg$)	1.5 (0.045)	2 (0.06)	3 (0.09)
Usable energy density from H_2 (net useful energy/max system volume)	kWh/L ($kg\ H_2/L$)	1.2 (0.036)	1.5 (0.045)	2.7 (0.081)
Storage system cost [e]	$\$/kW_eh$ net ($\$/kg\ H_2$)	6 (200)	4 (133)	2 (67)
Fuel cost [f]	$ per gallon gasoline equivalent at pump	3	1.5	1.5
Operating ambient temperature[g]	°C	-20/50 (sun)	-30/50 (sun)	-40/60 (sun)
Cycle life (1/4 tank to full)[h]	Cycles	500	1000	1500
Cycle life variation[i]	% of mean (min) @ % confidence	N/A	90/90	99/90
Minimum and Maximum delivery temperature of H2 from tank	°C	-20/100	-30/100	-40/100
Minimum full flow	(g/sec)/kW	0.02	0.02 FC 0.027 ICE	0.02 FC 0.033 ICE
Minimum delivery pressure of H2 from	Atm (abs)	2.5 FC	2.5 FC	2 FC

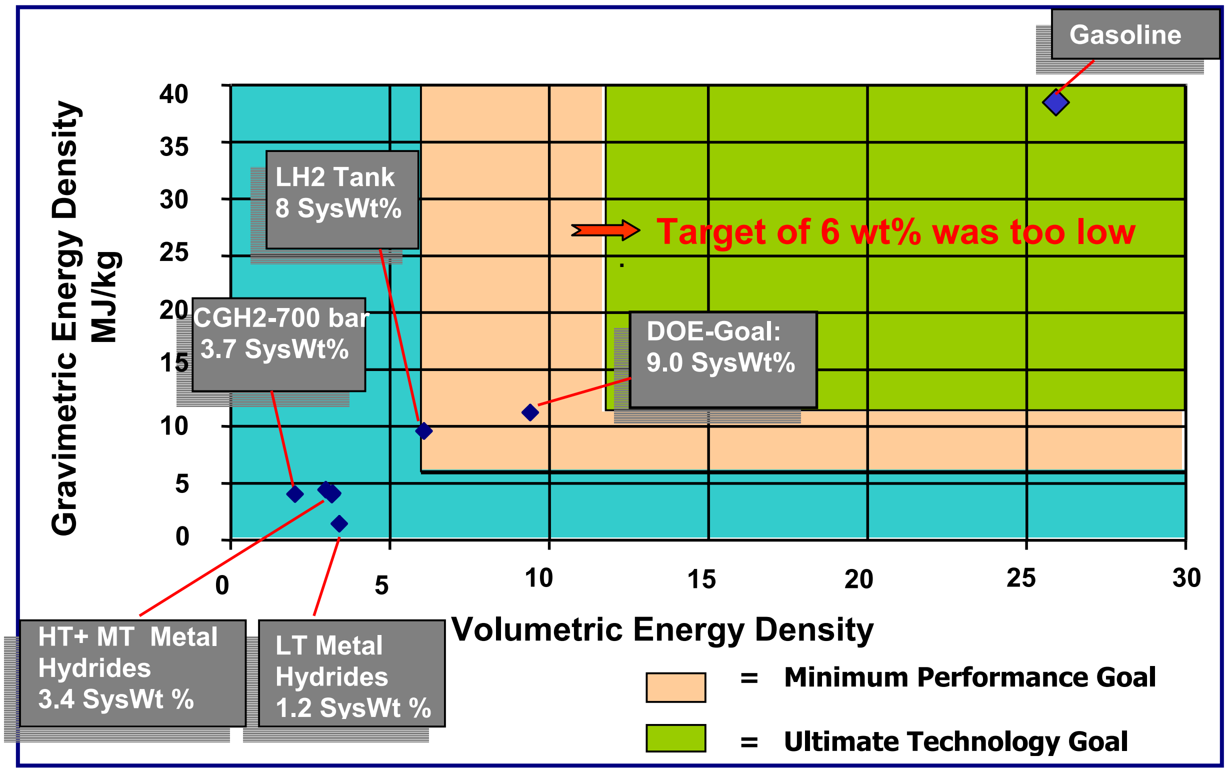
Technical Targets, On-Board Hydrogen Storage Systems [A, B, C]				
Storage Parameter	**Units**	**2005**	**2010**	**2015**
tank FC=fuel cell, I=ICE		10 ICE	35 ICE	35 ICE
Transient response 10%-90% and 90%-0% [j]	Sec	0.5	0.5	0.5
Start time to full flow at 20°C	Sec	4	0.5	0.5
Start time to full flow at minimum ambient	Sec	8	4	2
Refueling rate[k]	kg H_2/min	0.5	1.5	2
Loss of useable hydrogen[l]	(g/hr)/kg H_2 stored	1	0.1	0.05
Permeation and leakage[m]	SCCM/hr	Federal enclosed-area safety-standard		
Toxicity		Meets or exceeds applicable standards		
Safety		Meets or exceeds applicable standards		
Purity[n]		98%		

a. Based on the lower heating value of hydrogen and a minimum of 300-mile vehicle range; targets are for the complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity and/or other balance-of-plant components.
b. Unless otherwise indicated, all targets are for both internal combustion engine and for fuel cell use, based on the low likelihood of power-plant specific fuel being commercially viable.
c. Systems must be energy efficient - for reversible systems, greater than 90% energy efficient; for systems generated off-board, greater than 70% life-cycle efficiency. Useful constants: 0.2778 kWh/MJ, 33.3 kWh/gal gasoline equivalent.
d. Generally the 'full' mass (including hydrogen) is used, for systems that gain weight, the highest mass during discharge is used.
e. 2003 U.S. $; total cost includes any component replacement if needed over 15 years or 150,000 mile life.
f. 2001 U.S. $; includes off-board costs such as liquefaction, compression, regeneration, etc; 2015 target based on H_2 production cost of $1.50/gasoline gallon equivalent untaxed.
g. Stated ambient temperature plus full solar load
h. Equivalent to 100,000; 200,000; and 300,000 miles respectively (current gasoline tank spec).
i. All targets must be achieved at end of life
j. At operating temperature.
k. 2015 target is equivalent to 3-5 minutes refueling time.
l. Total hydrogen lost from the storage system, including leaked or vented hydrogen; relates to loss of range.
m. Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with CSA/NGV2 standards for vehicular tanks. This includes any coating or enclosure that incorporates the envelope of the storage system.
n. For fuel cell systems: less than 10 ppb sulfur, 1ppm carbon monoxide, 1 ppm carbon dioxide, 1ppm ammonia, 100 ppm hydrocarbons; oxygen, nitrogen and argon can not exceed 2% on a dry basis.

Workshop on Hydrogen Storage Materials

An automotive original equipment manufacturer's systems level perspective on on-board hydrogen storage was discussed. The basis was the plenary presentation given by General Motors at the Workshop on Hydrogen Storage Materials that was held at Argonne National Laboratory on August 14th and 15th 2002. The key message was, based on the status of current technology, none of the storage technologies being developed in the DOE program is applicable to a broad range of vehicle platforms. Figure 3 illustrates the hydrogen storage requirements for vehicle applications; it is slightly modified from that presented at the ANL workshop. The minimum acceptable performance for one or two light-duty vehicle platforms is 6 MJ/L and 6 MJ/L. To meet the needs of a broad range of vehicle platforms, the goal is about 12 MJ/L and 12 MJ/L. (These targets were subsequently modified by the FreedomCAR Hydrogen Storage Technical Team, which includes representatives from DaimlerChrysler, Ford, GM, and DOE.) These volumetric and gravimetric densities correspond to fully packaged storage systems, not solely the storage medium.

FIGURE 3. HYDROGEN STORAGE REQUIREMENTS AND STATUS FROM AN OEM PERSPECTIVE



Storage Tank Baseline Design and Technology Status

Mr. James of Directed Technologies, Inc. presented baseline designs for 350 bar (5000 psi) and 700 bar (10,000 psi) Type 4 all-composite tanks and compared these designs with the DOE technical targets. The Directed Technologies 2001 status estimate of high-pressure hydrogen tank technology showed that the volumetric energy storage density was deficient by a significant percentage and that the cost was an order of magnitude too high. The potential issues related to high-pressure storage tank technology were presented as a point of departure for the workshop discussions.

Workshop Discussion

A pressure of 700 bar was considered the best path to achieve the DOE targets with on-board compressed hydrogen storage. However, the participants felt that a compelling argument has not yet been made for a specific pressure that accounts for both on-board and off-board infrastructure issues. A study that considers volume, cost, weight, compressor cost and efficiency, infrastructure burden and the supply chain would have value. However, in order to have viable 750 bar designs, development and optimization of 350 bar tanks needs to continue to maturity. Standards are currently in place for 350 bar operation and need to be extended to 750 bar.

Quantum

Neel Sirosh summarized Quantum's tank development indicating that their 700 bar tank is rated for 15,000 cycles and achieves 6.5% H_2 mass fraction (bottle only). With future structural modifications, 7.8% H_2 mass fraction could be achieved. Failure modes at 700 bar are not well understood and a better understanding of failure modes may allow structural optimization, leading to lighter, stronger and cost-effective tanks.

Lincoln Composites (General Dynamics)

Norm Newhouse presented an overview of Lincoln Composites' (now part of General Dynamics) tank technology and its remaining development issues. He also presented Canadian work on tank sensors that may hold promise for the development of "smart" tanks that could provide an on-board, real-time measure of a storage tank's "state of health".

Lawrence Livermore National Laboratory

Salvador Aceves summarized the Lawrence Livermore National Laboratory work to develop pressurized cryogenic storage tanks. Cryogenic tanks that can withstand elevated pressure can reduce hydrogen loss due to boil-off over extended storage periods. Cost effective designs are being developed. Andrew Weisberg presented ideas for radical shapes for hydrogen containers that may better utilize the volume available for hydrogen storage on-board a vehicle. Radical shapes may also serve to distribute the high-pressure over smaller volumes and /or in various cage structures. Several smaller volumes of hydrogen contained at high-pressure may provide greater margins of safety compared to one or two larger on-board tanks.

The workshop participants identified new and improved materials and resins research for liners and tanks as critical to further reductions in cost and weight. Metal/ceramic composites for ancillary components, low cost engineered fibers and materials capable of cryogenic conditions should be investigated. The participants cited the need for the emergence of a tank component supply chain as key in achieving cost effective tank systems that are robust, safe and acceptable to consumers.

A fundamental understanding of the safety issues related to hydrogen fuel on board a vehicle was identified as a high priority for further R&D. Data from a statistical number of tanks that have been failure tested should be developed. Existing data related to tank failures needs to be collected and analyzed. Measurements of the pressure wave resulting from a tank failure and its effect on the vehicle and occupants are needed. The workshop identified the need to understand component failure modes related to on-board tank storage systems. This includes not only the tank but also the regulators, valves and connectors. Some of the participants thought a reduction in the burst/safety factor to 1.8 could be supported if used in conjunction with a smart tank safety system with embedded sensors that have the capability to detect incipient damage and limit fill pressure until repairs could be made. The achievable mass fraction could then increase to 8.1%. There is a need for gathering centrally-located safety data bank for reference by the tank community, specifically data from work at the national laboratories and independent test organizations. Tests should be conducted in an independent facility that has the capability to test tanks to failure under realistic scenarios. Data should be shared within the community where possible. The DOE could play an important role to provide funds for this research.

Safety of on-board high-pressure tank systems depends on a reliable vehicle-tank interface during refueling. Development of standardized refueling interface hardware and software is required. For this to happen, experimental data on interface component performance and failure modes must be developed to support standards development activities. The participants agreed that a hydrogen-fueled vehicle should be in control of on-board safety and not be reliant on controls at a refueling station to ensure safe refueling.

The DOE hydrogen permeation rate target was discussed regarding its origins and whether it is appropriate for compressed and liquefied hydrogen storage tanks. Some of the workshop participants thought its origin was related to the specification for indoor gas-fired appliances. There is a need for studies on the thermal expansion of the tank liner relative to the outer tank at low pressure and at high temperature. Temperature changes during fast fill could present a challenge.

Table 2 below summarizes the consensus findings of the workshop participants. The topic area, recommended action and completion date for each of the recommended R&D topics were prioritized in the ranked order shown.

TABLE 2. COMPRESSED AND LIQUEFIED HYDROGEN STORAGE WORKSHOP FINDINGS SUMMARY

WORKSHOP FINDINGS SUMMARY			
RANK	**RESEARCH AREA**	**RECOMMENDED ACTIVITY**	**END DATE**
1	**Structural optimization of tanks, liners and components**	Better understanding of failure modes to optimize structural shell (lower weight and cost)	**2006**
2	**Vehicle H_2 Safety** • Pressure wave • Realistic failure scenarios • Fundamental understanding of failures R & D	• Collect existing statistics/data for hydrogen vehicle including failure modes of tanks • Extend standards to 700 bar • Test disposal nozzle • Measure pressure wave • Investigate friable matrixes that turn to dust upon failure • Develop component test facility • Measure impact durability at pressure • Investigate physical instabilities	**2005**
3	**Materials Research:** Materials composition and CTE at high pressure and low temperature	• Investigate metal / ceramic composites for ancillaries • Develop new resins • Develop lower cost engineered fibers • Trade-off strength versus cycle life • Study liner materials/design/processing	**2009**
4	**High-pressure balance of plant components :** tubing, fittings, check valves, regulators, mounting, filters, relief devices, shutoff valve and sensors	• Develop lighter, cost-efficient components and supplier base • Establish component test facility • Develop certification test protocol	**2005**
5	**“Smart tank & storage systems”** (note Canadian work already exists)	• Develop sensing technologies that enable lower burst pressure ratio and cycle life requirements • Achieve consumer acceptability • Participate in education and outreach	**2005**
6	**Refueling strategy**	• Develop interface hardware and software systems to enable a vehicle to control safety independently of the fueling infrastructure • Develop thermal management strategies for fast full fills	**2006**
7	**Containment shapes with internal structure utilizing continuous fiber fabrication**	• Demonstrate radical conformable containment structures to reduce tank mass by factor of 2 to 5	**2009**

WORKSHOP FINDINGS SUMMARY			
RANK	**RESEARCH AREA**	**RECOMMENDED ACTIVITY**	**END DATE**
8	**Hydrogen leakage rates:** Permeation through liner both at ambient and cryogenic temperatures	• Investigate permeation rates through liner materials • Revise technical targets	**2004**
9	**Active cooling for hydrogen**	• Investigate on and off board cooling	**2009**
10	**Fueling station economics**	• Study throughput needed to achieve economic operation	**2004**

Appendix A. Plenary Presentations

Overview Presentation

Hydrogen Storage Tank Workshop

Walter F. Podolski – ANL
JoAnn Milliken - DOE

USCAR
October 16, 2002

Workshop Agenda

- 9:00 am Welcome and introductions
- 9:15 DOE Hydrogen Storage Summary
- 9:45 Workshop deliberations
- 12:00 pmLunch
- 12:45 Workshop deliberations
- 3:00 Summarize findings and prepare recommendations
- 5:00 Adjourn

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Presentation Outline

- Workshop Objectives
- The Hydrogen, Fuel Cells, and Infrastructure Program
- Role of FreedomCAR
- R&D Priorities
- DOE Fuel Cell & Hydrogen Activities
- DOE Targets/Status
- ANL H_2 Storage Workshop Summary

Workshop Objectives

- Summarize the status of hydrogen storage tank technology
- Identify and prioritize technical challenges relating to hydrogen storage tanks
- Prepare rationale and recommendations for continued DOE-supported R&D
- Draft a research and development plan to overcome challenges that include go, no-go decision points

2

Hydrogen and Fuel Cells are a High Priority within EERE

National Energy Policy - **"Focus research and development efforts on integrating current programs regarding hydrogen, fuel cells, and distribution…"**

Hydrogen Vision/Roadmap Workshops held 2001 & April 2002 with industry stakeholders

- ✓ Hydrogen Vision complete
- ✓ Hydrogen Roadmap draft completed
- ✓ www.eren.doe.gov/hydrogen/features.html

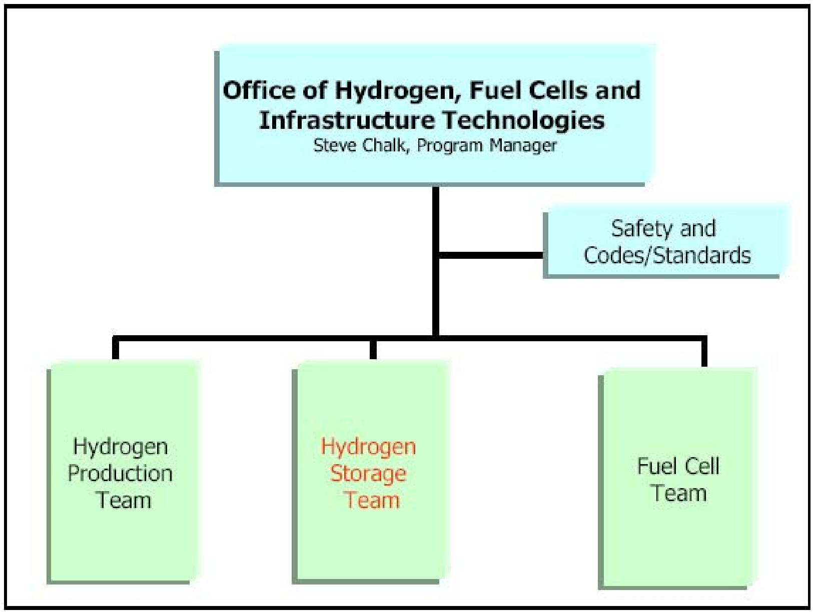
Technology development for hydrogen fuel cell vehicles is the thrust of the FreedomCAR Partnership

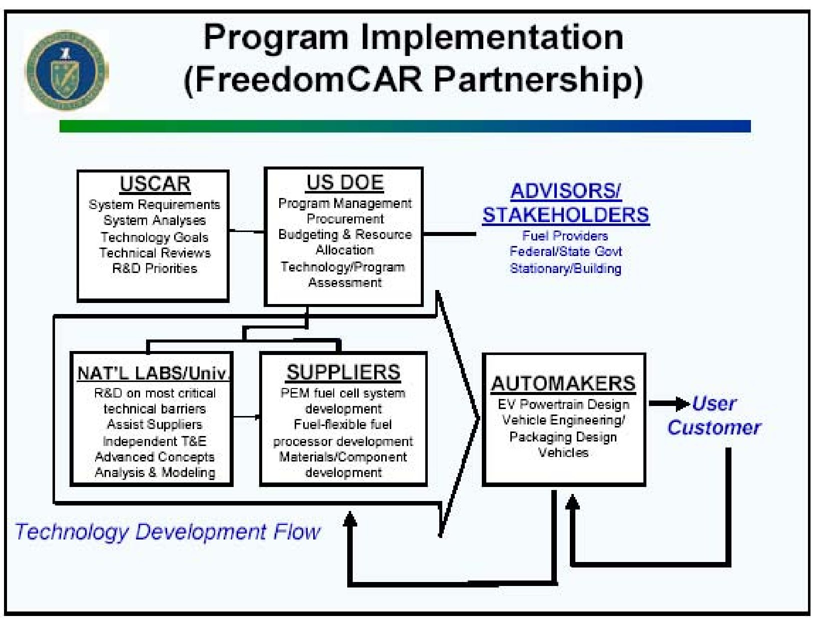
> ***"The President's Plan directs us to explore the possibility of a hydrogen economy…."***
> ***Spencer Abraham, Secretary of Energy***

Hydrogen and Fuel Cells Program R&D Priorities

1. ***Hydrogen Storage***
2. ***Hydrogen Production***
3. ***Fuel Cell Cost Reduction***

Safety & Codes/Standards, Education, and Vehicle/Infrastructure Testing and Validation will be areas which receive much greater attention


Office of Hydrogen, Fuel Cells and Infrastructure Technologies
Steve Chalk, Program Manager
Safety and Codes/Standards
Hydrogen Production Team
Hydrogen Storage Team
Fuel Cell Team


Program Implementation (FreedomCAR Partnership)
USCAR
System Requirements
System Analyses
Technology Goals
Technical Reviews
R&D Priorities
US DOE
Program Management
Procurement
Budgeting & Resource Allocation
Technology/Program Assessment
ADVISORS/ STAKEHOLDERS
Fuel Providers
Federal/State Govt
Stationary/Building
NAT'L LABS/Univ.
R&D on most critical technical barriers
Assist Suppliers
Independent T&E
Advanced Concepts
Analysis & Modeling
SUPPLIERS
PEM fuel cell system development
Fuel-flexible fuel processor development
Materials/Component development
AUTOMAKERS
EV Powertrain Design
Vehicle Engineering/ Packaging Design
Vehicles
User Customer
Technology Development Flow

4

DOE Technical Targets: On-Board Hydrogen Storage

	Units	Target	Status Physical Storage	Status Chemical Storage
Storage Weight Percent	%	6	5.2	3.4
Energy Efficiency	%	97	94	88
Energy Density	W-h/L	1100	800	1300
Specific Energy	W-h/kg	2000	1745	1080
Cost	$/kW-h	5	50	18
Operating Temperature	°C	-40–50°C	-40–50°C	20–50 °C
Start-Up Time To Full Flow	sec	15	<1	<15
Hydrogen Loss	scc/hr/L	1.0	1.0	1.0
Cycle Life	Cycles	500	>500	20-50
Refueling Time	min	<5	TBD	TBD
Recoverable Usable Amount	%	90	99.7	>90

EERE Fuel Cell and Hydrogen Funding ($K)

Interior Appropriations				
TRANSPORTATION FUEL CELL R&D	**FY 2001**	**FY 2002**	**FY 2003 Req.**	**Increase**
Systems	7,405	7,600	7,600	0 (0%)
Components	12,052	12,825	14,900	2,075 (+16%)
Fuel Processing & Storage	20,806	21,300	24,100	2,800 (+13%)
Field Evaluations	0	0	3,000	3,000 (New)
Technical Support Services	400	200	400	200 (+100%)
TOTAL	**40,663**	**41,925**	**50,000**	**8,075 (+19%)**
DISTRIBUTED GENERATION TECH.				
TOTAL, Stationary Fuel Cells	**5,440**	**5,500**	**7,500**	**2,000 (+36%)**
Energy & Water Appropriations				
HYDROGEN RESEARCH				
Core Research and Development	14,438	14,426	19,331	4,905 (+34%)
Technology Validation	9,009	10,320	15,000	4,680 (+45%)
Analysis and Outreach	3,147	4,437	5,550	1,113 (+25%)
TOTAL	26,594	29,183	39,881	10,698 (+37%)

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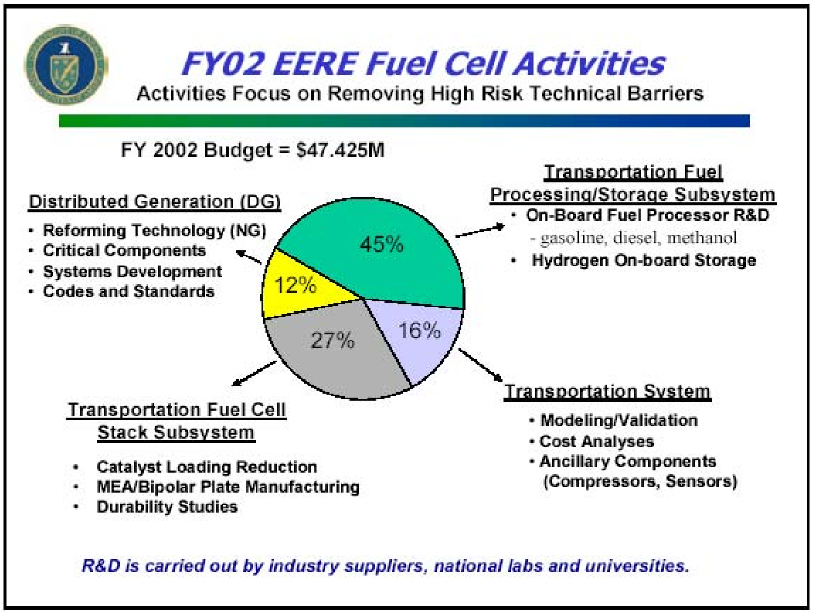
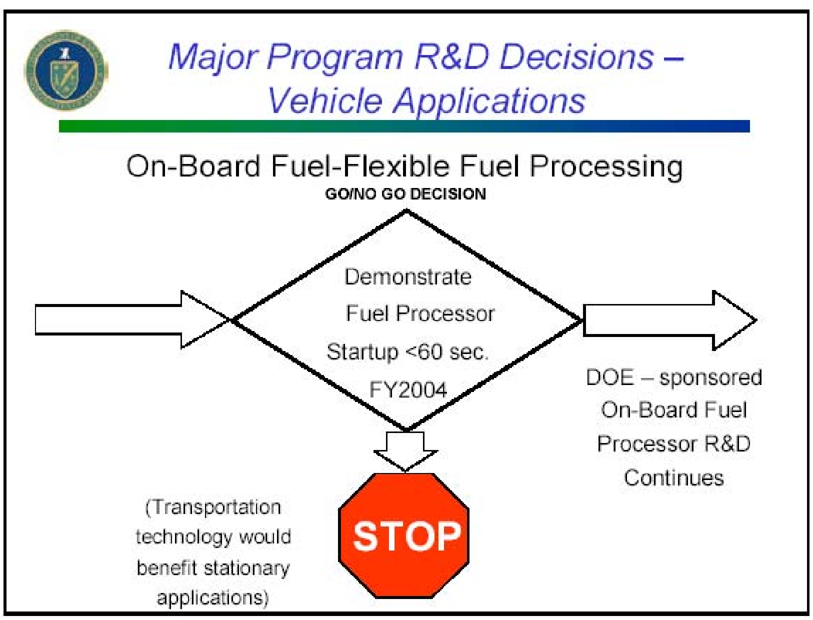
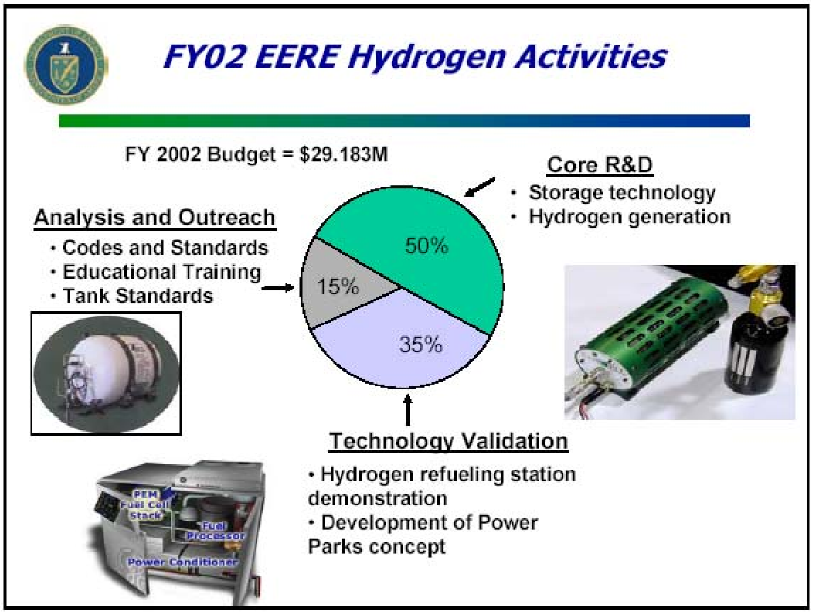
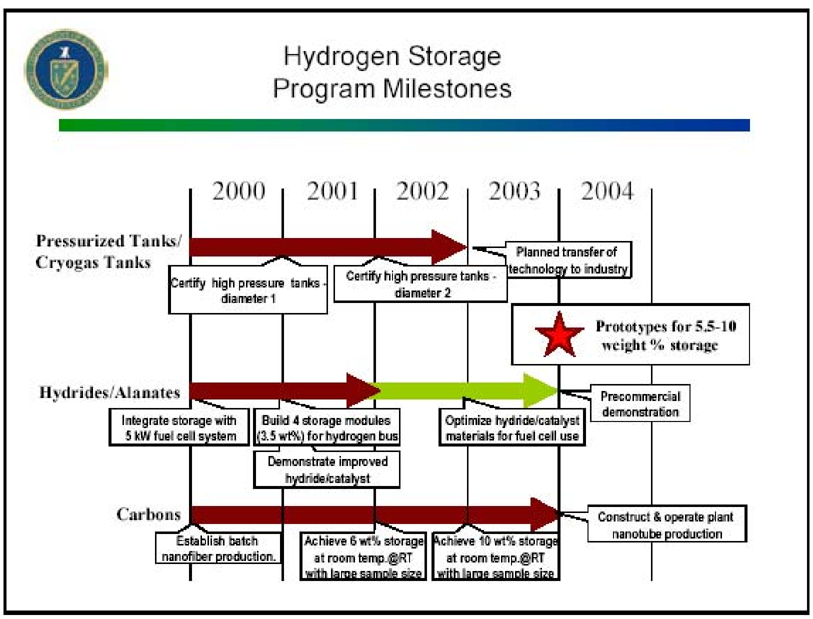

FY02 EERE Fuel Cell Activities
Activities Focus on Removing High Risk Technical Barriers
FY 2002 Budget = $47.425M
Distributed Generation (DG)
• Reforming Technology (NG)
• Critical Components
• Systems Development
• Codes and Standards
Transportation Fuel Processing/Storage Subsystem
• On-Board Fuel Processor R&D
- gasoline, diesel, methanol
• Hydrogen On-board Storage
45%
12%
27%
16%
Transportation Fuel Cell Stack Subsystem
• Catalyst Loading Reduction
• MEA/Bipolar Plate Manufacturing
• Durability Studies
Transportation System
• Modeling/Validation
• Cost Analyses
• Ancillary Components (Compressors, Sensors)
R&D is carried out by industry suppliers, national labs and universities.


Major Program R&D Decisions – Vehicle Applications
On-Board Fuel-Flexible Fuel Processing
GO/NO GO DECISION
Demonstrate
Fuel Processor
Startup <60 sec.
FY2004
DOE – sponsored
On-Board Fuel
Processor R&D
Continues
(Transportation
technology would
benefit stationary
applications)
STOP

6



FY02 EERE Hydrogen Activities
FY 2002 Budget = $29.183M
Core R&D
• Storage technology
• Hydrogen generation
Analysis and Outreach
• Codes and Standards
• Educational Training
• Tank Standards
50%
15%
35%
Technology Validation
• Hydrogen refueling station demonstration
• Development of Power Parks concept
PEM Fuel Cell Stack
Fuel Processor
Power Conditioner



Hydrogen Storage
Program Milestones
2000
2001
2002
2003
2004
Pressurized Tanks/ Cryogas Tanks
Certify high pressure tanks - diameter 1
Certify high pressure tanks - diameter 2
Planned transfer of technology to industry
Prototypes for 5.5-10 weight % storage
Hydrides/Alanates
Integrate storage with 5 kW fuel cell system
Build 4 storage modules (3.5 wt%) for hydrogen bus
Demonstrate improved hydride/catalyst
Optimize hydride/catalyst materials for fuel cell use
Precommercial demonstration
Carbons
Establish batch nanofiber production.
Achieve 6 wt% storage at room temp.@RT with large sample size
Achieve 10 wt% storage at room temp.@RT with large sample size
Construct & operate plant nanotube production

7

FY03 Planned Programmatic Highlights

Transportation:

- Continuation of R&D through 30 new cost-shared industry contracts and national laboratories to address key barriers
- Field Evaluations - Initiate activity to perform field evaluations of fuel cell vehicles in fleets

Distributed Generation:

- Major Procurement to be released in late FY02, awards mid-FY03
- Program will continue to focus on critical component and systems development

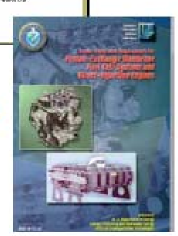
Hydrogen Program:

- Increased efforts in hydrogen storage and infrastructure in support of the FreedomCAR program
- Support for Power Parks and Uninterruptible Power Sources

'04 Transportation:

- Fuel processing Go/No Go decision

Previous DOE Workshops/Outcomes



Basic and Applied Research Needs for PEMFCs

- Established a high-temperature membrane (HTM) R&D program
  - LANL, multiple universities
  - Industry projects w/ 3M, UTC Fuel Cells, DeNora/DuPont
  - HTM Working Group
- Initiated projects to improve cathode
  - LANL, LBNL, Superior MicroPowders, other industry
- Expanded projects to reduce Pt content
  - NRL, BNL

Sensor Needs for PEM Fuel Cells and DI Engines

- Initiated a Sensor R&D Program
  - National Labs – LANL, LLNL
  - Industry – UTRC, Honeywell

Fuel Cells for Portable Power (January 2002)

- Proceedings/Solicitation to be released October 2002

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Hydrogen Storage Workshop

- Argonne National Laboratory
  - August 14-15, 2002
  - Attendees
    - 49 DOE/Laboratory
    - 32 Industry
    - 16 University
  - Plenary session
    - Automaker's perspective
    - Five overview presentations
  - Four breakout groups
    - Advanced/complex hydrides
    - Chemical storage
    - Carbon storage
    - Advanced concepts

Weight-Volume Comparison of Hydrogen Storage Systems

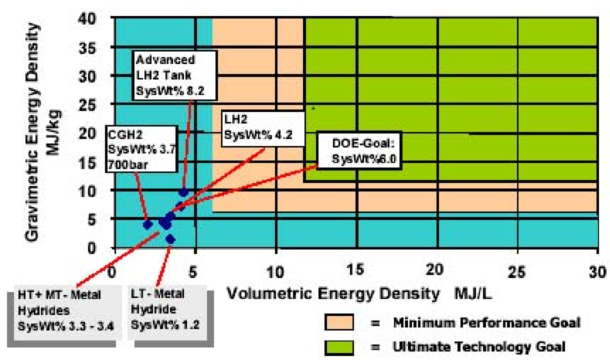

Chart courtesy of General Motors

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Advanced/Complex Hydrides-Targets

- $NaAlH_4$ capacity limited to about 5.6%
  - Interim goal (5-year) of 6%
- Need 8% hydrogen storage capacity for hydride if BOP adds 20 %
- 80% retained capacity after 500 cycles

Hydride R&D Recommendations

- Continue fundamental studies on $NaAlH_4$ as model system (2005)
- In parallel identify other hydride materials that have storage capacity greater than 6% (2007)
- Develop new materials to achieve 8 wt% (2010)
- Engineering analyses
  - Preliminary system cost analysis
  - Large scale material production
  - Independent safety consultant/laboratory to understand safety and certification issues

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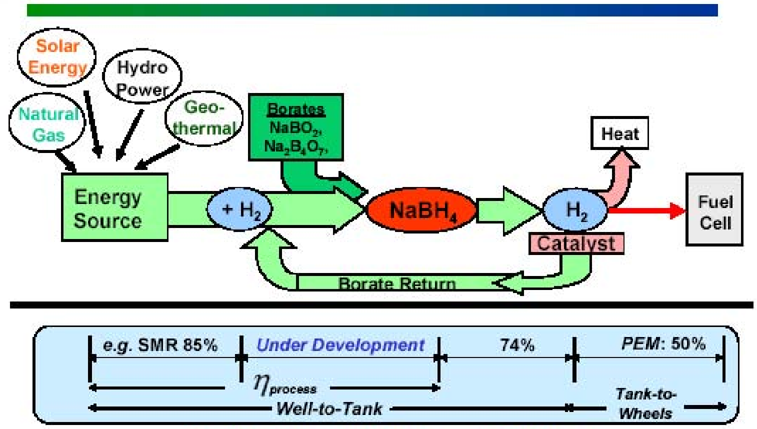
Chemical Hydride Storage R&D Recommendations

- Screen chemical complexes
  - Hydrogen storage density potential
  - Thermodynamic energy requirements including regeneration
- Improved/new process chemistry
  - Catalysts
  - Operating conditions (temperature, pressure)
- Well-to-wheels-to-well analysis of top complexes
  - Primary energy use
  - Cost of delivered fuel
  - Emissions
  - Resource depletion

Chemical Hydride Fuel Cycle



Well-to-Wheels Efficiency Targeted At 15 +%

Schematic courtesy of Millenium Cell

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Carbon Nanotube R&D Recommendations

- Conduct definitive experiments to show where and how hydrogen is stored in SWNT and for various forms of carbon materials
  - develop 2-3 pure SWNT standards for synthesis, purification, activation, and hydrogen adsorption/desorption
  - conduct round-robin testing
    - role of SWRI, other labs, universities, industry

Carbon Storage R&D Recommendations

- Need to understand the science to engineer carbon materials for hydrogen storage
  - Baseline theory to elucidate parameters affecting the number and type of binding sites and heat of reaction with for a broad range of (highly) modified carbon materials
    - effect of modifying shape, degree of curvature
    - chemical/electronic effects of additives and, defects
  - Provide "directional" guidance for experiments (and vice-versa)

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Advanced Storage Approaches Identified

1. Crystalline Nanoporous Materials
2. Polymer Microspheres
   Self-Assembled Nanocomposites
3. Advanced Hydrides
4. Metals – Organic
5. BN Nanotubes
   Hydrogenated Amorphous Carbon
6. Mesoporous materials
7. Bulk Amorphous Materials (BAMs)
8. Iron Hydrolysis
9. Nanosize powders
10. Metallic Hydrogen
    Hydride Alcoholysis

Overarching R&D Questions for All Advanced Materials

- Maximum storage capacity – theoretical model
- Energy balance / life cycle analysis
- Hydrogen absorption / desorption kinetics
- Preliminary cost analysis –
  potential for low cost, high volume
- Safety

Next Steps

- Prepare proceedings, including 5-year R&D plan
- Draft hydrogen storage solicitation
- Discuss advanced storage concepts further to refine recommendations and resolve controversial aspects

DOE Proposed H2 Storage "Off-Ramps"

2004 - R&D of cryogenic and high pressure hydrogen storage tanks

2004 - Go/No-Go Decision on Chemical Hydride Storage

2005 - Go/No-Go Decision on Carbon Nanotubes

2006 - Complex Hydrides downselected

2006 – Advanced hydrogen storage concepts downselected

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For More Information

www.anl.gov/g8
www.cartech.doe.gov/publications/2002hydrogen
www.eren.doe.gov/hydrogen/news
www.hydpark.ca.sandia.gov

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Storage Tank Design Straw man

Storage Tank Design

Brian James
Directed Technology, Inc.

Workshop on Hydrogen Storage Tanks
USCAR
October 16, 2002

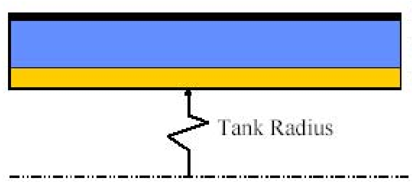
DOE Targets

Characteristic		Units	DOE Target	2001 Status
Storage Weight Percent		%	6	5.2
Recoverable Usable H2		%	90	99.7
Energy Density (gas)		W-h/L	1100	813
Specific Energy		W-h/kg	2000	1745
Cost		$/kW-h	5	50
Cycle Life		cycles	500	500
Operating Temperature		deg C	-40 to 90	-40 to 80
Start-up Delivery time to full flow				
	from 20deg C	sec	15	near zero
	from -20deg C	sec	30	TBD
Refueling Time		min	5	TBD
Hydrogen Loss		scc/h-L	1.0	TBD

Baseline Assumptions

		Workshop Baseline	
		5,000psi	10,000psi
Diameter ID	inches	8.6	8.6
Diameter OD	inches	18.7	19.5
Total Length	inches	62.7	39.1
Liner Material		HDPE	HDPE
Liner Thickness	inches	0.25	0.25
Fiber/Resin Material		T-700S	T-700S
Fiber/Resin Thickness (average)	inches	0.49	0.9
Fiber/Resin PF	inches	1.67M	1.67M
Abrasion Fiber thickness	inches	0.075	0.075

Type 4 Tank
5kg usable H2
SF=2.3
Fiber: T-700S
$8.50-$11/lb



DOE Targets

Characteristic	Units	DOE Target	2001 Status	Workshop Baseline	
				5,000psi	10,000psi
Storage Weight Percent	%	6	5.2	7.6%	7.8%
Recoverable Usable H2	%	90	99.7	97.5%	98.5%
Energy Density (gas)	W-h/L	1100	813	626	970
Specific Energy	W-h/kg	2000	1745	2,545	2,606
Cost	$/kW-h	5	50	10.6 (500 units)	11.4 (500 units)
				5.8 (500k units)	6.2 (500k units)
Cycle Life	cycles	500	500	500+ (?)	500+ (?)
Operating Temperature	deg C	-40 to 90	-40 to 80	? To +80deg C	? To +80deg C
Start-up Delivery time to full flow					
from 20deg C	sec	15	near zero	near zero	near zero
from -20deg C	sec	30	TBD	near zero	near zero
Refueling Time	min	5	TBD	<5min	<5min
Hydrogen Loss	scc/h-L	1.0	TBD	?	?

Potential Issues

- Thinner/Lighter Liners
  - no liner
  - new materials
- Tank Safety Factor
- Stronger Fibers
  - New feedstocks
  - New processing methods
- Fiber Strength Translation
  - New winding techniques
  - new resins
- Fiber Cost
  - new feedstocks
  - new processing methods
- High Temperature Resins

- Compression
  - cost
  - efficiency
- Solenoids
  - lighter weight
  - more reliable/higher safety
  - lower cost
- Tank/Station Interface

FreedomCar Storage Tech Team Workshop Page 5 DIRECTED TECHNOLOGIES INC

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